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Infrared Semiconductor Metamaterials

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Final Report

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metasurface, metamaterial, Mie resonator, optical antenna, reconfigurable, infrared

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Final Performance Report

AFOSR Grant # FA9550-13-1-0182

Title: **Infrared Semiconductor Metamaterials**

Principal Investigator: **Jon A. Schuller**

Grantee Institution: **UC Santa Barbara**

Grant Period: **July 15 2013 to July 14 2016**

Program Manager: **Harold Weinstock**

Executive Summary

The central objective of this program is to create a new class of programmable infrared optic that can steer or focus beams and is reconfigurable at electronic time scales. To achieve this goal, we must create subwavelength infrared "metasurface resonators" with a phase response that can be dynamically and continuousy tuned between 0 and 2π. The major achievements of this program are summarized below, along with associated development of research infrastructure that will form the basis of future research programs.

1) We have devised and demonstrated an approach for creating reconfigurable metasurfaces based on free-carrier refraction in high-index semiconductors. Modulation may be achieved with optical or electrical pumping. Research infrastructure: analytical Mie theory and Greens' function calculations; analytical and numerical simulations incorporating literature-based free-carrier materials models.

2) We have experimentally demonstrated ultra-wide tuning of resonance wavelengths in various semiconductor (InSb, InAs, Si, Ge) resonators. These effects demonstrate the more than order-unity changes in refractive index that can be brought about by modulating free-carrier concentrations. Research infrastructure: top-down and bottom-up methods for fabricating microdisk and spherical Mie resonators; infrared spectroscopy of individual subwavelength structures; (in progress) developing optical-pump infrared-probe measurements within FTIR system.

3) We have designed and demonstrated—with simulations—an electrically reconfigurable metasurface. This metasurface design fulfills the central objective of this proposal. Fabricating this metasurface and demonstrating its reconfigurable properties is the primary focus of subsequent AFOSR-funded research. Research Infrastructure: homebuilt simulation codes combining device and electromagnetics modeling, fabrication and preliminary measurements of tunable InSb and InAs resonators and metasurfaces.

Infrared Semiconductor Metamaterials

A. Central Objective

Metasurfaces, which can be thought of as optical frequency analogs of phased array radar, offer tremendous potential for constructing new classes of beam steering, shaping and focusing technologies. Metasurfaces and phased array optics are enabled by single "antenna" elements with controllable scattering, transmission, or reflection phase. Current methods for engineering phase rely on static geometry-based effects. In this YIP program we are searching for ways to *dynamically* tune the scattering phase of optical antennas and metamaterials. Dynamic tuning will enable reconfigurable photonic devices based on optical antenna and metamaterial concepts. The central goal of this work is to conceive, design, and implement an infrared nanoantenna system with continuous phase tuning between 0 and 2π. The potential of such an achievement is illustrated in Figure 1. A phase tunable metasurface resonator acts as the basic element of a programmable infrared optic that can steer or focus beams and is reconfigurable at electronic time-scales.

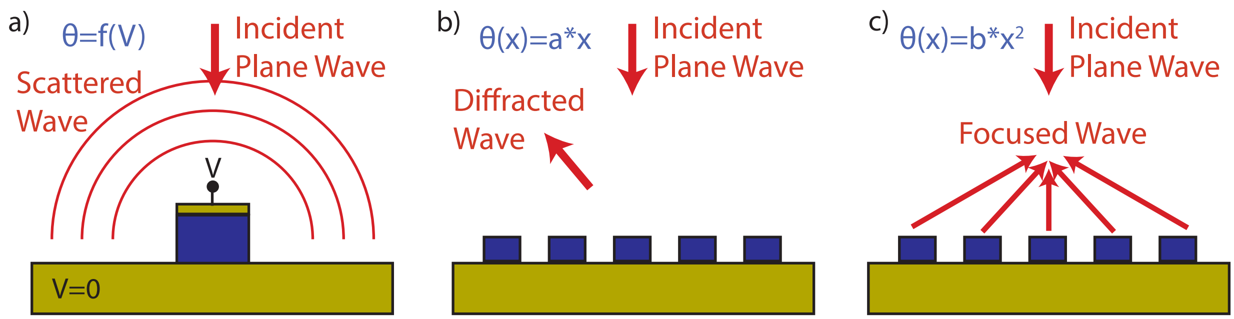

Figure 1. a) A subwavelength resonator whose scattering phase can be tuned between 0 and 2π forms the enabling element of a reconfigurable metasurface (i.e. phased array). b) In a resonator array, for instance, a linear phase profile redirects an incident plane wave into a unidirectional diffraction lobe. Changing the slope of this phase ramp electrically allows one to steer the direction of the diffracted beam. c) A quadratic phase profile with reconfigurable curvature produces a reflective focusing optic with variable focal length.

B. Major Achievement #1: Establishing an Approach for Widely Tunable Antennas and Metasurfaces

The key to creating reconfigurable metasurfaces is designing an antenna element in which transmission, reflection, or scattering phase can be continuously tuned between 0 and 2π with near-constant amplitude (Figure 1). The inability to achieve 2π phase control fundamentally stems from the nature of the underlying optical antennas. Because the light-matter interaction lengths are by definition subwavelength, and the quality factors modest ($Q \approx 1\text{–}10$), very large refractive index modulation is needed ($\Delta n \gtrsim 1$). Establishing a way to achieve such widely tunable properties was a foundational challenge of this program

Our solution for achieving phase tunable antennas and metamaterials is to use free carrier refraction in semiconductors. Materials such as Si, Ge, InAs, InSb, etc. are nearly lossless at infrared wavelengths (1.0-15 µm) and have relatively large infrared permittivities (~ 12-20). Subwavelength spherical and microdisc resonators made from these materials exhibit multipolar resonances that can be used to construct highly efficient metamaterials and metasurfaces. As free carriers are introduced, the permittiviy of the materials gets smaller, eventually becoming negative once the semiconductor has

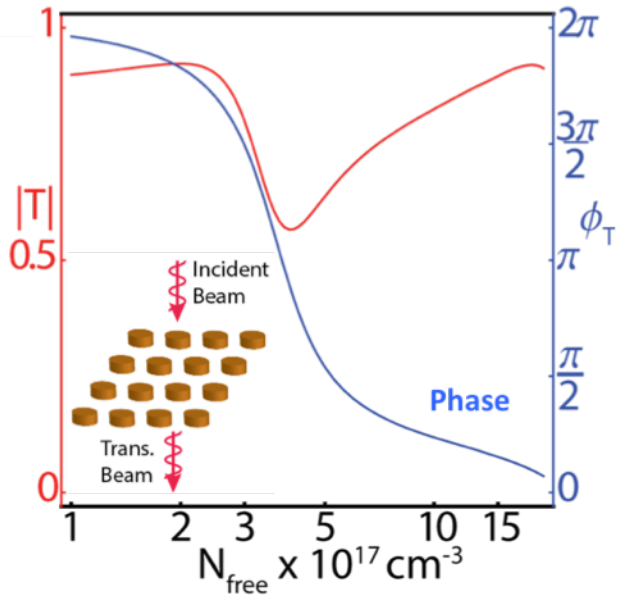

Figure 2. Transmission phase (blue) and amplitude (red) of an array of InSb microdisk Mie resonators for 10.6 micron wavelength. As the carrier density is tuned between 10^{17} and 10^{18} cm^{-3} the the transmission phase varies by 2π with nearly constant amplitude.

enough carriers to behave like a metal. In this program we have exploited this large degree of tunability to demonstrate widely tunable and reconfigurable antennas and metasurfaces.

Using analytical calculations and numerical simulations we demonstrated the possibility of using free-carrier dependent effects to construct phased-array metasurfaces. Our theory studies concentrate on InSb and InAs—where the small effective mass enables very large free-carrier refraction effects—but similar effects occur in Si and Ge as well. For instance, we demonstrated tuning of transmission phase through an array of InSB microdisk "Mie resonators" by modulating the free-carrier concentration over a modest range (Figure 2). **The transmission phase for a wavelength of 10.6 microns varies by 2π, with a minimal change in the transmission amplitude**. This work was recently published in ACS Photonics [1] where it was selected as an ACS Editors' Choice, an honor bestowed on only one paper per day across *all* ACS journals (e.g. JACS, Nano Letters, ACS Photonics, etc.), which represents less than 1% of total submissions. It is also the 4th most read ACS Photonics article over the last 12 months. (http://pubs.acs.org/action/showMostReadArticles?topArticlesType=recent&journalCode=apchd5)
In complementary studies of hybrid metal-semiconductor-metal antennas, we showed how free-carrier effects can alternately be used to make ideal "photonic resistors" by appropriate control of the carrier density [2].

These theory investigations demonstrated the power of free-carrier refraction for making widely tunable semiconductor-based infrared antennas and metasurfaces.

C. Major Achievement #2: Experimentally Demonstrating Widely Tunable Semiconductor Antennas

The theory studies described above are complemented by experimental studies of infrared semiconductor antennas. Mie resonators were fabricated with both top-down and bottom-up approaches. We developed an optical lithography approach for fabricating Si microdisks on both Si and SiO_2 substrates and experimentally demonstrated size-dependent Mie resonances across the mid-IR spectral range (2000-6000 cm^{-1}) [3]. Numerical simulations were used to identify the origins of these resonances, to explain observed differences between single-particle and particle-array spectra, and to identify unique phenomena arising from substrate-particle interactions.

Spherical Silicon and Germanium nanoparticles were fabricated via femtosecond laser ablation (Fig. 3 inset). The nanoparticles exhibit size-dependent magnetic dipole (MD) resonances throughout the infrared frequency range that match analytical Mie theory calculations. Undoped and lightly doped particles exhibit a linear relationship between size and resonance wavelength (symbols). Doping the particles beyond ~10^{18} cm^{-3} causes shifts in the MD resonance wavelength. The shifts agree with calculations (solid lines) that combine Mie theory with fit-free Drude (e.g. free carrier) models. As expected for Drude effects, the resonance shift is larger for resonances further in the IR (i.e. larger

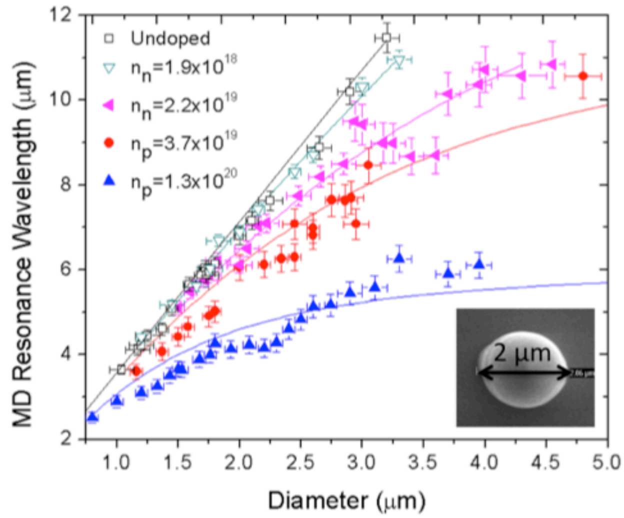

Figure 3. Spherical semiconductor particles are fabricated via femtosecond laser ablation (inset). Experimentally determined magnetic dipole (MD) resonance wavelengths are plotted versus size for different doping levels. Doping the particles induces huge wavelength shifts that agree with our derived models (solid lines).

particle sizes) where the effect of free carriers is more significant. **These findings demonstrate the potential for actively tuning infrared Mie resonances by optically or electrically modulating charge carrier densities**, thus providing an excellent platform for tunable metamaterials. These results were published in Nano Letters [4] and selected by Nature Photonics as a "Research Highlight".

D. Major Achievement #3: Designing and Demonstrating Electrically Reconfigurable Metasurfaces Based on Heterojunction Resonators.

To *dynamically* achieve the widely tunable antenna and metasurfaces described above we need an approach to dynamically vary electron densities in InSb and InAs resonators between ~ 10^{17}-10^{18} cm^{-3}. Achieving such large modulations in charge carrier density electrically is challenging but feasible. The central challenge arises from the need to modulate high carrier densities over large distances (order 1 μm), which makes conventional depletion-mode devices insufficient.

We overcome this limitation with novel InAs/AlGaSb and InSb/InAlSb heterojunction designs. These heterojunctions use electron and hole blocking layers to accumulate large electron concentrations under forward bias. The heterojunction devices are MBE-grown and then fabricated into arrays of individually addressable 1-dimensional Mie resonators. By applying different voltages across the array we can make fully reconfigurable metasurfaces as illustrated schematically in Figure 1. We use a home-built, combined device and electromagnetics simulation platform to model the behavior of such a voltage-controlled metasurface. An example result is shown in Figure 4. A spatially-varying voltage profile is used to create a linear phase-ramp across the array of resonators. This linearly varying reflection phase produces a unidirectional diffraction lobe. **The combination of subwavelength periodicity and full 2π tuning of individual resonators enables any arbitrary choice of diffraction angle.** Specific cases where the phase profile is periodic across an integer number (n) of resonators are easiest to simulate and shown for 3<n<12. In each case a high quality uni-directional diffraction lobe is produced with very little power in unwanted side lobes. These results were published in Advanced Optical Materials July 2016 [5]. The manuscript was a top-5 most downloaded paper for July-August 2016 (http://www.materialsviews.com/advanced-optical-materials-top-5-august-2016/) and was highlighted in Materials Views (http://www.materialsviews.com/researchers-propose-new-route-programmable-infrared-optics/).

E. Ongoing & Future Work: Dynamically Tunable Antennas and Metasurfaces

Ongoing and future work building off this young investigator program is focused on dynamically reconfigurable metasurfaces. We are pursuing three distinct approaches. We are constructing **Electrically Reconfigurable** metasurfaces following the route described in section D. This work is the primary focus of an AFOSR grant set to begin September 30, 2016. This central approach is complemented by ongoing investigations of **thermally** and **optically** reconfigurable metasurfaces.

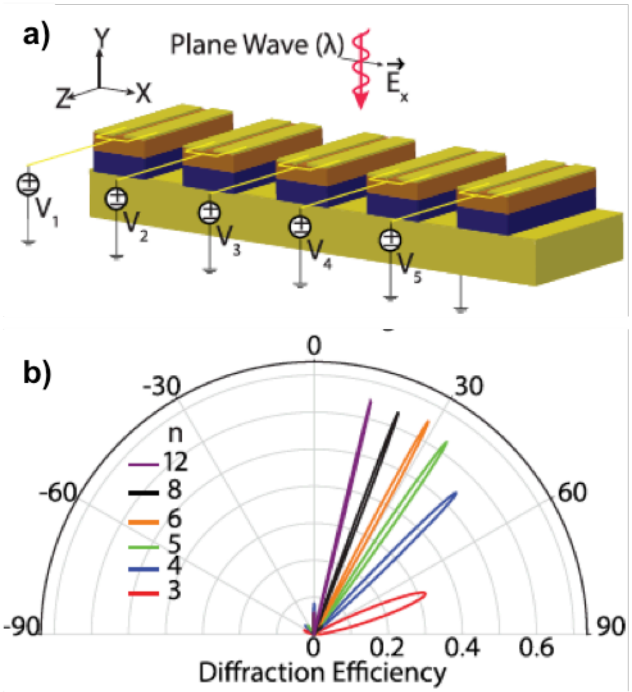

Figure 4 a) An array of individually addressable 2π-tunable InSb/InAlSb heterojunction Mie resonators forms a reconfigurable metasurface. **b)** Combined device and electromagnetics simulations demonstrate high quality diffraction lobes produced by electrically programming a linear phase ramp across the array. The beamcan be continuously steered; cases are shown where the phase is periodic with an integer number (n) of resonators.

F. Relevance to Air Force Objectives

This research program addresses the Air Force's objective to develop more efficient and selective optical communications and imaging components. Novel techniques, materials, and devices operate at infrared wavelengths (1.0-15 µm), addressing technologically important communication bands including telecom (1.3-1.7 µm) and atmospheric transparency (2.0-2.5; 3.0-4.0; and 8-12 µm) wavelengths. At these frequencies the semiconductor materials considered here have negligible optical losses, allowing for the construction of metamaterials with nearly zero internal dissipation. Most importantly, as demonstrated in this report, the electromagnetic response can be tuned optically or electrically through free carrier refraction effects. Thus, these results represent a critical first step towards the ultimate realization of nearly lossless, reconfigurable metamaterial-based devices.

G. Publications Acknowledging AFOSR Support

[1] Iyer, P.P., Butakov, N.A. and Schuller, J.A. Reconfigurable semiconductor phased-array metasurfaces. *ACS Photonics*, **2**, 1077-1084 (2015).

[2] Butakov, N.A. and Schuller, J.A. Hybrid optical antennas with photonic resistors. *Optics Express*, **23**, 29698-29707 (2015).

[3] Butakov, N.A. and Sculler, J.A. Designing multipolar resonances in dielectric metamaterials. *Scientific Reports* (in review).

[4] Lewi, T., Iyer, P.P., Butakov, N.A., Mikhailovsky, A.A. and Schuller, J.A. Widely tunable infrared antennas using free carrier refraction. *Nano Letters*, **15**, 8188-8193 (2015).

[5] Iyer, P.P., Pendharkar, M. and Schuller, J.A. Electrically Reconfigurable Metasurfaces Using Heterojunction Resonators. *Advanced Optical Materials*, available online (2016).

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Jon Schuller

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Abstract

The central objective of this program is to create a new class of programmable infrared optic that can steer or focus beams and is reconfigurable at electronic time scales. To achieve this goal, we must create subwavelength infrared "metasurface resonators" with a phase response that can be dynamically and continuousy tuned between 0 and 2π. The major achievements of this program are summarized below, along with associated development of research infrastructure that will form the basis of future research programs.

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[5] Iyer, P.P., Pendharkar, M. and Schuller, J.A. Electrically Reconfigurable Metasurfaces Using Heterojunction Resonators. Advanced Optical Materials, available online (2016).

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